Sediment addition and legume cultivation result in sustainable, long-term increases in ecosystem functions of sandy grasslands

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ABSTRACT

Desertification of sandy grasslands is an increasing problem, with serious negative impacts on ecosystem functions. Sandy grasslands are fragile with low ecosystem productivity mainly because of the sandy soil structure with low water and nutrient holding capacities and especially low levels of nitrogen. Here, we evaluate the long-term impacts of sediment addition from a local reservoir, and grass and legume cultivation (artificial grasslands) on a sandy grassland in eastern Inner Mongolia, China. The results showed that, even after 32 years, sediment addition had improved soil structure significantly, i.e. increasing of silt and clay contents, soil bulk density, and water holding capacity. As the result of improved soil structure, ecosystem functions, including aboveground net primary productivity (ANPP) and soil carbon, nitrogen (N) and phosphorus storage increased significantly. Net C, N and P sequestration increased even after accounting for the sediment addition, due, at least partially, to the greater plant biomass trapping large quantities of wind-blown dust. Plant cultivation, especially the addition of a legume, further increased ANPP significantly, i.e. the cultivation of *Leymus chinensis* and the legume *Medicago sativa* increased ANPP 6.99 and 44.62 times, respectively. Our study highlights that improvements in soil structure and cultivation with legume species can increased substantially the productivity of sandy grasslands, and that the initial increases in grass biomass promoted the sequestration of wind-blown dust which helped sustain the increases in productivity.

KEY WORDS: land degradation, grassland restoration, soil structure, water holding capacity, carbon sequestration

INTRODUCTION

Sandy grasslands are grasslands growing on coarse-textured soil (sand contents generally equal to or greater than 50%), and cover approximately 1.44×10^5 km^2 in Inner Mongolia, China (Zhao et al., 2007). They have been widely used as pastureland or farmland and are important socio-economically and ecologically. However, almost half of the sandy grasslands in China had been substantially degraded in the last 50 years (Li, Zhao, Liu, & Huang, 2008), due to the consequences of both direct human activities and climate change. In particular, livestock over-grazing, over-cutting, land-use change (conversion of natural grasslands to croplands) and overuse of groundwater have promoted major loss of ecosystem function (Wang et al., 2018). Degradation in sandy grasslands has serious negative impacts on many aspects of ecosystem services and, therefore, is considered an important ecological and environmental problem both regionally and globally (Dlamini, Chivenge, Manson, & Chaplot, 2014; Ru et al., 2018). Thus, investigating approaches for restoring or maintaining ecosystem services within sandy grassland is of great significance (Wang et al., 2018).

In these grasslands, the sandy soils are characterized by low water- and nutrient-holding capacities, limiting primary production (Knapp, Briggs, & Koelliker, 2001). Furthermore, the high sand contents of the soils results in them being particularly susceptible to severe wind and water erosion (De Boer, Deru, & Van Eekeren, 2018), and the amount and quality of new dust inputs is very important for replacing eroded material and maintaining soil microbial diversity and ecosystem productivity (Gupta & Germida, 2015; Hao et al., 2017; Wang, Brewer, Shugart, Lerdau, & Allison, 2018). Critically, because the loss of productivity in sandy grasslands has been shown to be mainly caused by soil degradation (Schoenholtz, Van Miegroet, & Burger, 2000) improvement of soil structure may be key for restoring and enhancing the productivity of these ecosystems.

Sediments within rivers or lakes often have high organic matter, nutrients and clay contents

(Gudasz et al., 2010; Insam, Gomez-Brandon, & Ascher, 2015). The addition of such sediments to sandy grasslands may have the potential to improve soil physical and bio-chemical properties such as soil structure, porosity, humus content, water and nutrient holding capacity (Ebabu et al., 2019; Oldfield, Wood, & Bradford, 2018). Furthermore, lakes and reservoirs located in the same regions as sandy grasslands often infill rapidly as a result of high rates of soil erosion (Yuan, Ouyang, Zheng, & Xu, 2012). Removing sediments from the lakes and reservoirs is a common management approach used to maintain water supplies (Gao, Li, Chen, Ban, & Gao, 2019). Thus, adding such sediments from nearby lakes and reservoirs may be a potential approach for improving soil structure and ecosystem functions in sandy grasslands. However, with reservoir sediments still representing a limited resource, this approach is only likely to have potentially widespread utility if any benefits of sediment addition for sandy grassland productivity are maintained for extended time periods.

To control degradation and protect the regional environment, some measures (e.g. planting indigenous trees and shrubs, planted grasslands, natural recovery) to recover ecosystem function have been implemented in China recent decades (Li et al., 2018; Su, Li, Cui, & Zhao, 2005; Wu, Liu, Zhang, Hu, & Chen, 2010). Of particular relevance for sandy grasslands, cultivation of previously arable land with perennial grasses and legumes is now being adopted (Chen, He, Tang, Zhao, & Shao, 2016). Legume cultivation may be particularly beneficial because the productivity of sandy grasslands in China is considered to be mainly limited by nitrogen (N). While fertilizer-use efficiency has been shown to be very low in the ecosystems, because of the low nutrient holding capacity of the soils (Zeng et al., 2010), legume species have been found to potentially increase N availability and community productivity in sandy grasslands (Herben et al., 2017; Spehn et al., 2005) to a greater extent than the use of fertilizers (Torabian, Farhangi, & Denton, 2019). While both ecological and economic benefits have been demonstrated, the area of sandy grasslands planted with legumes remains very small in China relative to Europe and New Zealand. Furthermore, to our knowledge, no study has examined the combined effects of sediment addition and legume cultivation on sandy grassland productivity. Information on these aspects is required for a better understanding of how sandy grassland productivity is controlled and the relative roles that changes in soil structure and legume cultivation could play in restoring degraded systems.

Here we present the results from a long-term (32-yr) sediment addition and plant cultivation experiment in the Keerqin sandy grasslands of northern China. Our objectives are: (1) to determine whether sediment addition can improve soil structure in the long term in sandy grasslands; (2) to examine the effects of soil structure improvement on soil water holding capacity and ecosystem functions, including aboveground net primary productivity (ANPP), carbon (C), N, and phosphorus (P) storage and sequestration; and (3) to determine whether plant cultivation (especially the use of legumes) can further increase grassland productivity.

MATERIALS AND METHODS

Study site

The experiments were conducted at Zhanggutai Station located in Northern China in a representative eastern Keerqin sandy grassland (42˚42' N, 122˚ 32' E). The experimental site was established and maintained by the Institute of Sand Land Improvement and Utilization in Liaoning Province, China. The mean annual temperature is 7.3°C, and the mean annual precipitation is 450 mm, with a lowest and highest recorded annual precipitation of 224.8 mm and 661.3 mm, respectively (Chen, Zeng, & Fahey, 2009). The altitude of the study site is 226.5 m.a.s.l. Soils are aeolian sandy soils according to IUSS Working Group WRB (2007). The vegetation consists of forb species (e.g., *Artemisia capillaries*, *A. frigida*, and *A.sacrorum*), grasses species (e.g., *Pennisetum flaccidum* and *Cleistogenes chinensis)*, and shrubs (e.g., *Caragana microphylla*, *Prunus sibirica,* and *Lespedeza davurica).*

Experimental setup

In 1979, a sandy grassland site of 100 ha was selected for establishing the experimental plots. There were four treatments, each with three replicate plots of 6 ha (Table 1), including Control (natural sandy grassland), sandy grassland amended with sediment (S), plots cultivated with a dominant perennial grass, Chinese rye grass (*Leymus chinensis*), together with added sediment (LC+S), and plots cultivated with the legume, alfalfa (*Medicago sativa*), plus the added sediment (MS+S). For the sediment addition treatment, we applied 300 Mg ha^{-1} of sediment and mixed the sediment with top soil to a depth of 40 cm by plowing in 1979. The sediment used in this study came from the bottom of a nearby reservoir. The removal of sediments from reservoirs takes place every autumn in this region of China because soil erosion decreases the water holding capacity of lakes and reservoirs. The sediment contained 13.83% C, 0.625% nitrogen (N), and 0.090% phosphorus (P) by mass. Therefore, the total rates of C, N and P addition in the sediment were: 41.49 Mg C ha^{-1}, 1.88 Mg N ha^{-1} and 0.27 Mg P ha^{-1}, respectively. For the treatments of LC+S and MS+S, the natural vegetation was destroyed by plowing to a depth of 40 cm before sowing with target species in 2005. *L. chinensis* and alfalfa were sown with seeds at density of 60 kg ha^{-1} and 30 kg ha^{-1} respectively. All the plots were mowed once a year (5 cm left), but there was no additional management in the plots, such as grazing, fertilization or irrigation. In the treatments of LC+S and MS+S, there were few other species present and *L. chinensis* and alfalfa contributed more than 90% of the biomass in their respective treatments.

Field sampling, ANPP and soil physical property measurements

In mid-September of 2011, we randomly chose five 1 × 1 m quadrats within each plot. Annual ANPP was estimated by clipping to ground level, after removing the previous year's litter. All living vascular plants were sorted to species, dried and weighed. The dry mass of all plant species per quadrat was averaged over the three plots to estimate ANPP. Within each quadrat, three soil cores to the depth of 100 cm were collected, and cut into five layers: 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, and 60-100 cm. Soil samples from the same plot were then composited by sieving through a 2-mm mesh and roots were removed.

Three plastic pots (10 cm in diameter. and 10 cm in depth) were driven into the soil in each plot to a depth of 10 cm to collect and measure rates of dust input from the atmosphere. The dust inputs were collected monthly for one year, from May 2011 to April 2012. The dust was weighed and analyzed for C, N, and P content to calculate total C, N and P inputs.

Soil texture, bulk density and water-holding capacity (WHC) of 0-10 cm soils were analyzed. The measurements of sand, silt and clay content were performed by the hydrometer method (Gee & Bauder, 1986). Soil bulk density, the mass of dry soil per unit of bulk volume, including the air space, was measured using a core method (Petrovic et al., 1982). WHC was measured by soaking the soil samples in water for 2 h and then draining for 2 h (Wierbicki & Deatherage, 1958). The samples were weighed (W_0), then dried at 105°C for 24 h and weighed again (W_1) in order to calculate WHC (%) = 100 * (W_0- W_1)/ W_1.

Chemical analyses

Organic C concentration of soil samples and dust inputs were measured using a modified Mebius method (Nelson & Sommers, 1982). Specifically, 0.5 g of ground soil was digested with 5 ml of 1 N $K_2Cr_2O_7$ and 10 ml of concentrated H_2SO_4 at 180°C for 5 min, followed by titration with $FeSO_4$ standard solution. The N concentration was measured using the modified Kjeldahl wet digestion procedure (Gallaher, Weldon, & Boswell, 1976). Samples were digested in 75-ml graduated Pyrex test tubes that fitted into the electrically heated Al block. Glass funnels (25 mm) were placed in the mouth of the 1-inch diameter test tubes to ensure efficient refluxing of the digest mixture and to prevent loss of H_2SO_4. After cooling, the samples were brought to 50-ml volume in the tubes with deionized H_2O, mixed using a vortex test-tube mixer, and analyzed for N using a 2300 Kjeltec Analyzer (FOSS, Sweden). Total P concentrations were determined using the ammonium molybdate method after persulfate oxidation (Kuo, 1996). Samples were digested with H_2SO_4 and $HClO_4$ using the same tubes as those used for total N concentrations. The solutions were treated with ammonium molybdate and P concentrations determined colorimetrically using a spectrophotometer (Shimadzu UV2700).

Calculation of C, N, and P storage

We calculated total stocks of soil organic C (SOC) (Mg C ha^{-1}), soil total N (STN, Mg N ha^{-1}), and soil total P (STP, Mg P ha^{-1}) to the depth of 100-cm using the following equations:

(1) $SOC = \sum D_i \times P_i \times OC_i \div 100$

(2) $STN = \sum D_i \times P_i \times TN_i \div 100$

(3) $STP = \sum D_i \times P_i \times TP_i \div 100$

where D_i, P_i, OC_i, TN_i and TP_i represent the soil thickness (D, cm), bulk density (P, g cm^{-3}), organic C concentration (OC, %), total N concentration (TN, %) and total P concentration (TP, %) at the i_{th} layer, respectively; i = 1, 2, 3, 4, and 5 for the 5 depth increments outlined above. In order to characterize the soil C, N, and P sequestration capacity after the experimental treatments, net soil C, N, and P sequestration of 0-40 cm and 0-100 cm soils were calculated as follows: for the 0-40cm layer: total C/N/P storage minus the C/N/P in the added sediment and the C/N/P storage in the control plots; for the 40-100 cm layer: total C/N/P storage minus the C/N/P storage in the Control plots.

Statistical analysis

An analysis of variance (ANOVA) with Tukey HSD was used to assess the effect of experimental treatments on soil bulk density, WHC, ANPP, soil clay, silt and sand content, C N, and P storage and sequestration, and dust inputs. All statistical analyses were performed by using the SPSS program, ver. 10.0 (SPSS Inc.; Chicago, IL, USA).

RESULTS

Significant improvements in soil texture were still observed 32 years after the sediment was added, with increases in clay and silt contents, soil bulk density, and water holding capacity (Fig. 1). In particular, water holding capacity was increased 56% by sediment addition. Cultivation with *L. chinensis* or alfalfa did not result in any further significant changes in these soil physical characteristics, in comparison to sediment addition alone (Fig. 1). Both sediment addition and cultivation of plants had significant effects on above-ground net primary productivity (ANPP); compared with the control, ANPP increased by factors of 2.70, 6.99 and 44.62 for the S, LG+S and MS+S treatments, respectively. Sediment addition also increased soil C, N, and P storage significantly (Fig. 2) Cultivation with legumes also significantly increased C storage in MS+S in the whole soil profile (Fig. 2), and N storage in two of the five sampling depths (Fig. 3). Cultivation with *L. chinensis* did not increase C, N or P storage compared with adding sediment treatment alone.

After subtracting C, N and P stocks in Control plots and inputs from sediment, net C sequestration was observed in the top 100cm of all the sediment addition treatments (Fig. 2). Furthermore, net C, N and P sequestration totals were substantial throughout the soil profile, being greater in the 40-100 cm layer than in the 0-40 cm layer (Table 2). The sequestration of C and N under alfalfa was significantly greater than for the other two sediment treatments, but there was no effect of cultivation on P sequestration (Fig. 2).

Due to increases in plant biomass resulting in greater interception of wind-blown dust, all of the sediment addition plots experienced greater rates C, N and P inputs from dust than in the controls (Fig. 4), with rates of input being increased by a factor of 200. Significant differences were also observed between the sediment addition treatments, with C, N, and P inputs being greatest in MS+S plots, but the LC+S treatment showed slightly, but significantly, lower rates of input compared with the S treatment.

DISCUSSION

Sandy grasslands are fragile ecosystems, which have been substantially degraded, and present major challenges for restoration (Chen et al., 2012; Godefroid, Le Pajolec, Hechelski, & Van Rossum, 2018). The main reason that sandy grasslands provide low ecosystem services is that their soils have extremely low silt and clay contents, and thus low water and nutrients holding capacity (Schapel, Marschner, & Churchman, 2018; Wang et al., 2018). In this study, even after 32 years, sediment addition improved soil structure significantly (Fig. 1), increasing soil bulk density, clay and silt contents (Hao & Kravchenko, 2007). The improved soil structure and water holding capacity increased ecosystem functions including ANPP, soil C, N and P storage, sequestration and dust inputs. While previous studies have identified positive correlations between soil texture, nutrient retention and ecosystem productivity in sandy grasslands (Mendelssohn & Kuhn, 2003; Su, Wang, Yang, Yang, & Fan, 2015; Zhang et al., 2018), to our knowledge, this is the first time that sediment amendment has been shown to be able to have long-term positive impacts on grassland productivity in China.

The sediment addition significantly increased C, N, and P stocks in the soil profile (0-100 cm) (Fig. 2). Even after subtracting the C, N, and P in the added sediment, substantial rates of net C, N, and P sequestration were observed. The rates of sequestration were also much higher than that found in some previous research in grasslands (He et al., 2012; Jones, Rees, Kosmas, Ball, & Skiba, 2006). Previous experiments have also shown that grazing management can aid recovering of sandy grasslands in this region (Li et al., 2012). For example, compared with lightly grazed grasslands in Inner Mongolia, three decades of grazing exclusion resulted in 3.84 Mg C ha^{-1} yr^{-1} of SOC sequestration in the 0-100 cm soil layer (He, Yu, Wu, Wang, & Han, 2008), and Conant et al. (2001) reported that changes in grazing management and fertilization can lead to annual increases of 3.77 Mg C ha^{-1} in C stocks in the 0-100 cm soil layer. Grazing exclusion tends to promote a rapid increase in soil organic matter storage, followed by a steady phase of C and N sequestration with time; the rapid increase of C and N in the former phase may be partially explained by increases in litter input, root production and turnover (Conant et al., 2001; Guo, Wang, & Gifford, 2007; He et al., 2008). However, in our study, the control plots were not grazed, with all plots being only mowed once per year. Therefore, the gains in C, N and P storage that we observed were in addition to the exclusion of grazing animals, demonstrating how effective sediment addition and plant cultivation were in increasing ANPP, soil C, N, and P storage and sequestrations in these sandy grasslands.

There are two main factors that help explain the increased C, N, and P storage and sequestrations of soils in this sandy grassland. First, ANPP with sediment addition increased significantly due to enhanced nutrient and soil water holding capacity. Based on the increased aboveground biomass, it is likely that increased litter input and belowground biomass contributed to increased C content and sequestration (Guo et al., 2007). Second, the improved ANPP along with the higher coverage and height of plants help to reduce wind and water erosion (He et al., 2012; Li, Hao, Zhao, Han, & Willms, 2008), and promoted the interception of wind-blown dust (Fig. 4), which contains more C, N, and P than sand. In this study, based on one year of data, dry dust inputs may have contributed more than half of the total amount of soil C sequestration, and potentially the majority of soil N and P sequestration, implying that it is very important to prevent soil erosion and increase the vegetation coverage to improve soil C, N and P sequestration.

Our study showed that soil C storage increased significantly in the deeper soil layers, with rates of sequestration below 40 cm comparable to those observed in the 0-40 cm soil layer, which was different from typical grasslands (Li, Yu, Li, & Zhou, 2016; Zeng et al., 2010). This could be due to greater C transport to deeper layers in sandy soils, i.e., with the high porosity of the sandy soils (Yuan et al., 2012), fine particles with higher nutrient contents can be transported to deeper soil depths through the flow of water. Another possible reason is that rates of decomposition may be slower due to lower oxygen and higher soil moisture levels in deep soils (Carter, 2005; Dolan et al., 2006). These phenomena could be important mechanisms for soil C sequestration of sandy grasslands. In addition, the interception of wind-blown dust likely means that these soils were accruing vertically, which may explain some of the apparent sequestration at depth. Unfortunately, most previous studies on C sequestration in sandy grasslands have focused only on the 0-20 cm or 0-40 cm soil layers (Chen et al., 2012; Li et al., 2008; Zhou, Li, Zhao, & Drake, 2008). Therefore, more studies on C, N and P cycling in deeper soils in sandy grassland are needed.

Soil N availability is a limiting factor for plant growth in sandy grasslands (Chen et al., 2009). Our study showed that cultivation of alfalfa resulted in the highest ANPP. This may have been due to the greater rates biological N fixation as suggested by increase in greater rates of N sequestration in the MS+S plots compared to the other sediment addition treatments (Fig. 2). Soil C sequestration was also higher under cultivation of alfalfa than other treatments due to the greater plant productivity. Many previous studies have also showed that the presence of N fixers increased ANPP in different ecosystems (De Deyn et al., 2009; Flombaum & Sala, 2008), and that legumes can enhance soil C and N contents and C sequestration (Conant et al., 2001; He, Han, & Yu, 2011). However, overall, N addition has been found to have only minor effects on C sequestration due to high rates of N leaching in many ecosystems with low water and nutrient retention capacities (Lu et al., 2011). Thus, the substantial increase in C and N in MS+S treatment is likely not only due to simply to the greater rates of N-fixation, but also because the improved soil physical properties allowed some of the added N and C to be retained. In addition, it is important to emphasise that there was no irrigation in our plots and therefore the large increase in ANPP under alfalfa was likely caused by the increased water-holding capacity of the soils, and also potentially by alfalfa accessing water stored at depth as has been shown for plants in some sandy grasslands (Sharma, 1991).

Almost half of the sandy grasslands in China has been substantially degraded mainly due to over-grazing and conversion of grasslands to croplands (Li et al., 2008). These degraded sandy grasslands can recover with natural restoration, but this is a very slow process (Li et al., 2011) due to the low water and nutrient holding capacity of soils and the limited nutrients (Zeng et al., 2010). The one-off sediment application still promoted a 3-fold increase in productivity >30 years later, even in comparison to control plots from which grazing was excluded. The sediment used in this study came from the bottom of a reservoir in the studied area, which also benefited the capacity of the reservoir. There are more 6461 lakes, receiving 1.5×10^8 Mg sediments per year in Inner Mongolia based on a survey in 2010 (Ma & Wu, 2010). There is the potential for improving 5000 km^3 sandy grasslands per year with this amount of sediment. Although it can be difficult to add sediment to some sandy grasslands, our study suggests that this approach, in addition to others (e.g., adding super absorbent polymers) (Yang, Yang, Chen, Guo, & Li, 2014), can enhance productivity and increase soil C sequestration in sandy grasslands through improved soil physical structure, soil water and nutrient holding capacity, enhancement of dust inputs and decreased water and wind erosion.

In conclusion, we have shown that the combined addition of sediments and cultivation of legume species increased ecosystem productivity, and carbon and nutrient storage substantially, and thus represents a viable approach for reducing degradation and improving ecosystem services in sandy grasslands. While sediment addition cannot be carried out everywhere, targeted applications, in combination with legume cultivation, could help restore key areas within these degraded landscapes, with major benefits for sandy grassland management in Inner Mongolia.

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Figure Legends

Figure 1 Bulk density, water holding capacity and physical structure characteristics of soils (0-10cm) and annual aboveground net primary productivity (ANPP) under different management practices. See text and Table 1 for experimental treatments in detail. Different letters indicate significant differences among experimental treatments at $P < 0.05$. The error bars indicate +1 SE.

Figure 2 Soil C, N, and P stocks and net changes in the 0-100 cm soil layer under different management practices. See text and Table 1 for experimental treatments in detail. Different letters indicate significant differences among experimental treatments at P <0.05. The error bars indicate +1 SE.

Figure 3 Soil C, N, and P storage in five soil layers under different management practices. See text and Table 1 for experimental treatments in detail. Different letters indicate significant differences among experimental treatments at $P < 0.05$. The errors bar indicate +1 SE.

Figure 4 Atmospheric C, N, and P inputs in dust under different management practices. See text and Table 1 for experimental treatments in detail. Different letters indicate significant differences among experimental treatments at P <0.05. The error bars indicate +1 SE.

Table 1 Experimental treatments and land-use history

Treatment	Sediment addition (kg ha^{-1})	Cultivation	Description
Control	No	No	Natural sandy grassland without experimental treatment
S	3×10^5	No	Sandy grassland amended with sediment in 1979 without cultivation
LC+S	3×10^5	*Leymus chinensis*	Sandy grassland amended with sediment in 1979 and *Leymus chinensis* cultivation since 2005
MS+S	3×10^5	*Medicago sativa*	Sandy grassland amended with sediment in 1979 and *Medicago sativa* cultivation since 2005

Note: S is the abbreviation of sediment.

Table 2 Soil C, N and P sequestration in the 0-40 cm and 40-100 cm soil layers relative to un-manipulated sandy grassland (Control).

	C sequestration (Mg C ha^{-1})	N sequestration (Mg N ha^{-1})	P sequestration (Mg P ha^{-1})
0-40 cm			
S	14.91 ± 8.47^{NS}	0.18±0.04*	0.27 ± 0.09*
LC+S	5.68 ± 10.37^{NS}	-0.72 ± 0.12**	0.11 ± 0.08^{NS}
MS+S	57.24 ± 13.33*	0.58 ± 0.0.34^{NS}	0.27 ± 0.06*
40–100 cm			
S	77.91 ± 13.11**	2.14 ± 0.31**	0.70 ± 0.06**
LC+S	31.26 ± 16.02^{NS}	2.05 ± 0.48*	0.59 ± 0.20*
MS+S	55.33 ± 21.70*	2.10 ± 0.46*	0.56 ± 0.04**

† Data represent the mean and 1 SD of absolute changes in soil C, N, and P storage (n = 3). The amounts of C, N and P added with sediment (0-40cm) were subtracted from that in sediment amended plots.

‡Two-tailed t test (n=3) indicated no difference (NS) and differences significant at $P < 0.05$ and $P<0.01$.

Fig. 1

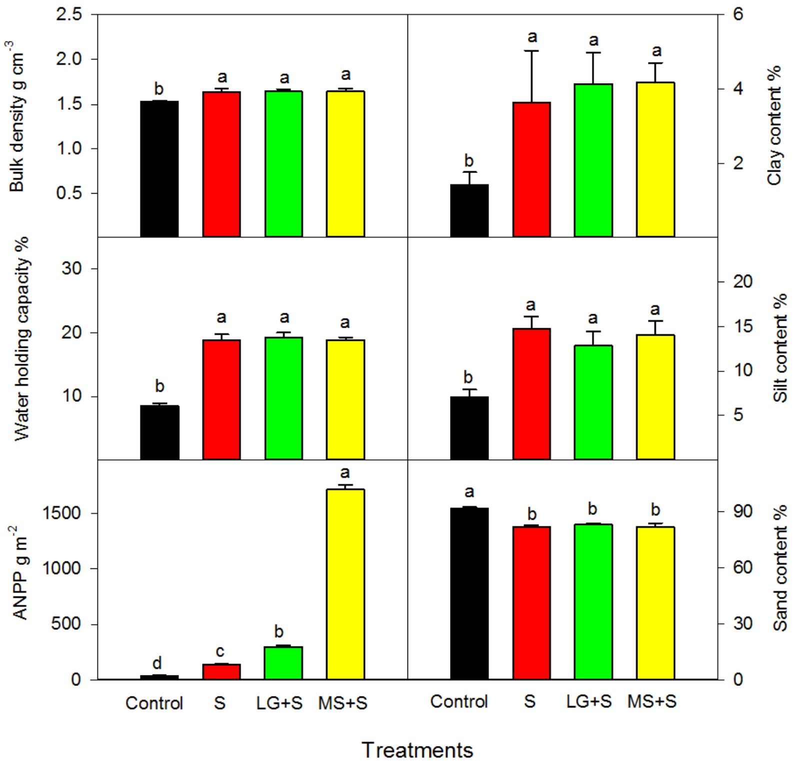
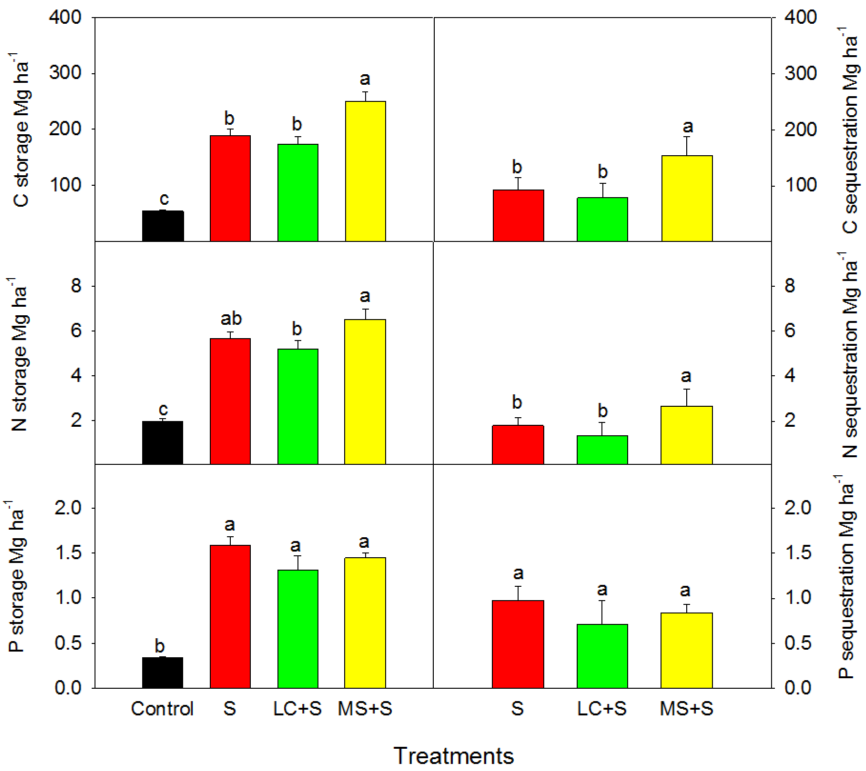

Bulk density g cm-3
Clay content %
Water holding capacity %
Silt content %
ANPP g m-2
Sand content %
Control
S
LG+S
MS+S
Treatments

Fig. 2



C storage Mg ha-1
N storage Mg ha-1
P storage Mg ha-1
C sequestration Mg ha-1
N sequestration Mg ha-1
P sequestration Mg ha-1
400
300
200
100
8
6
4
2
2.0
1.5
1.0
0.5
0.0
c
b
b
a
b
b
a
c
ab
b
a
b
b
a
b
a
a
a
a
a
a
Control
S
LC+S
MS+S
S
LC+S
MS+S
Treatments

Fig. 3

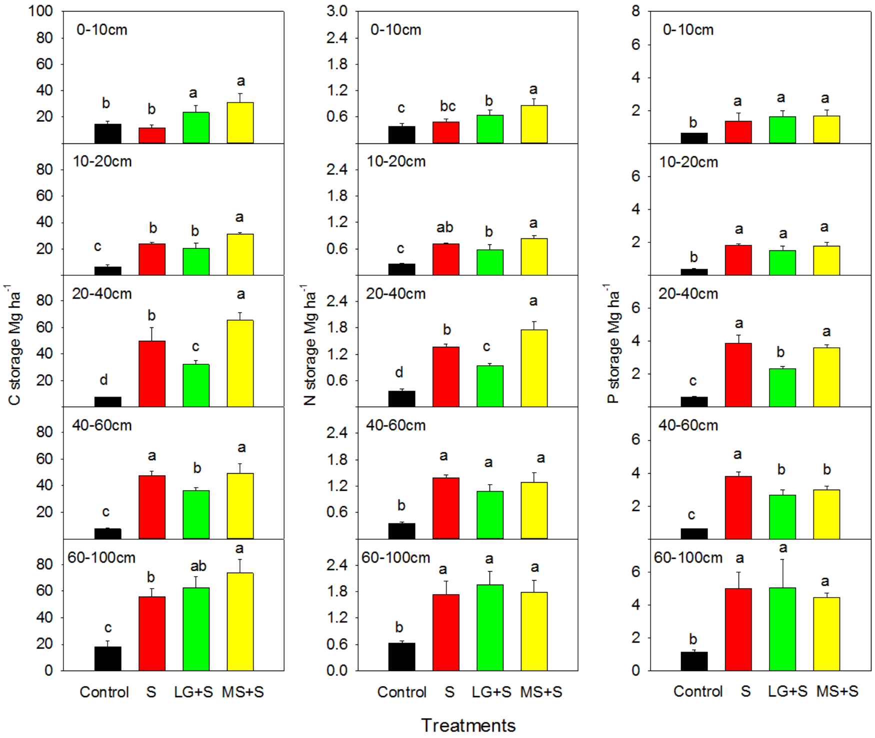
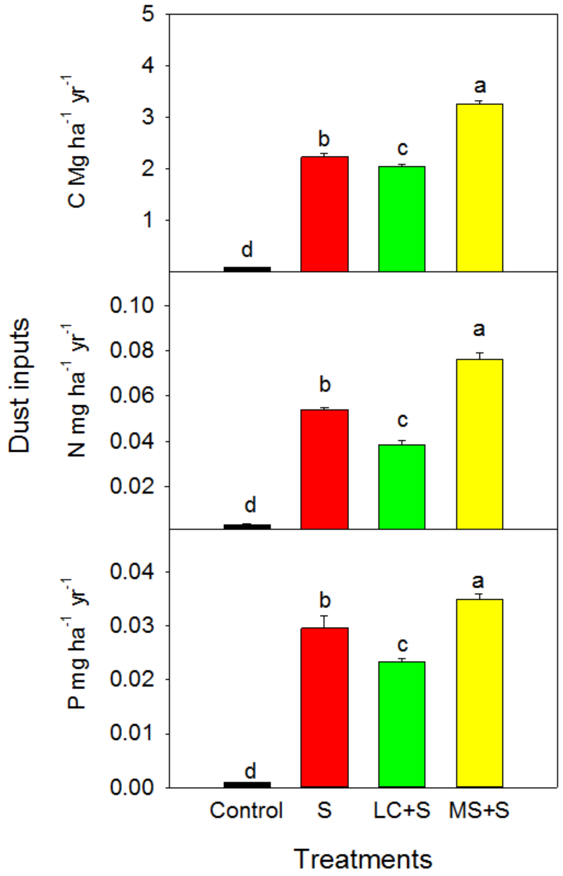

C storage Mg ha^{-1}
N storage Mg ha^{-1}
P storage Mg ha^{-1}
0-10cm
10-20cm
20-40cm
40-60cm
60-100cm
Control
S
LG+S
MS+S
Treatments

Fig. 4



Dust inputs
C Mg ha-1 yr-1
N mg ha-1 yr-1
P mg ha-1 yr-1
5
4
3
2
1
0.10
0.08
0.06
0.04
0.02
0.04
0.03
0.02
0.01
0.00
a
b
c
d
Control
S
LC+S
MS+S
Treatments